# Both improvements of the light extraction efficiency and scattered angle of GaN-LED using sub-micron Fresnel lens array

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## ABSTRACT

With the demanding requirements for light source, light emitting diodes (LED) attracts more and more attention because of its inherent advantages such as low power consumption, high reliability and longevity. However, there are two disadvantages for LED, one is the low light extraction efficiency resulting from the total internal reflection, and the other is the relative large scattered angle. In order to improve the light extraction efficiency and collimate the out-coupling light, a sub-micron Fresnel lens array is introduced and investigated in this paper. The focal length of the proposed Fresnel lens is 3μm and the minimum width of the outmost ring is about 150nm. To calculate and analyze the light extraction efficiency and the scattered angle of LED with such Fresnel lens array structure, we optimize the parameters of the Fresnel lens, such as the depth of the Fresnel lens array structure and the thickness of the p-type gallium nitride layer by using the finite difference time domain method (FDTD). By comparing the discussed patterned GaN-based LED with that traditional flat LEDs, it can be found that significant enhancement factor of the light extraction efficiency, which is improved by 3.5 times, can be obtained and the scattered angle at half maximum can be decreased 50° from 60° with this novel Fresnel lens structure. It will be expected that the proposed sub-micron structure can find wide applications in LEDs industry.

**Key words:** LED, light extraction efficiency, scattered angle, Fresnel lens array

## 1. INTRODUCTION

In order to obtain better visual effect, the requirement of the light source is improved simultaneously. LED, a new generation of green environmental light source, due to its advantages like longer life time, narrow spectral emission band and low operating voltage, has been seemed as an ideal light source for displayers. Besides, it is so small that can be used in portable applications. In this paper, we aim to develop a kind of LED light source which can be used in projective illumination. For achieving this goal, the light extraction efficiency needs to be improved while the scattered angle should be narrowed.

Meeting the brightness requirements of the applications is the main challenge in developing LED-based projection systems[1].Take the GaN-LED as an example, its light extraction efficiency is only a few percent which is partly resulted from the limited critical angle of 24 degrees at the interface of p-GaN and air. Photons emitted beyond this angle will be internally confined due to the effect of total reflection. Many investigations have been made in this respect, such as texturing the emitting surface [2-5], using a patterned substrate [6], generating photonic crystals in LEDs [7-10] and some other special structures [11]. All these structures can realize the improvement of light extraction efficiency, but due to the diffraction effects, the scattered angle will have a certain increase [2]. This increase is not what we want. On the other hand, a catadioptric system is usually adopted so as to collimate the output beam from LED [12-15]. Such system can make the scattered angle of LED to be narrowed to only several degrees; however it can not improve the light extraction efficiency, and then cannot meet the brightness requirement. In addition, LED with such system is a bit big, so it can not be used in small devices.

Here, a sub-micron Fresnel lens array is presented to improve the light extraction efficiency and collimate the output beam at the same time. It was found that this sub-micron Fresnel lens array on the top layer of the diodes with optimized

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parameters can significantly enhance the output light intensity and decrease the scattered angle of GaN-based blue LED. In the simulation, the light intensity is increased about 3.5 times and the scattered angle is decreased to 10 degrees when it is compared with that of a conventional LED.

## 2. METHODOLOGY

In this study, the finite difference time domain (FDTD) method was employed to simulate the far-field intensity distribution of the LED with and without investigated structure on the p-type gallium nitride layer. Figure 1 shows the model of a GaN-based LED unit with a Fresnel lens. In this model, from bottom to top, each layer is followed by aluminum (thickness is 0.3 microns), the sapphire substrate (thickness is 1 microns), n-type gallium nitride, luminous layer, p-type gallium nitride and Fresnel lens, the total thickness of the rear three layers is 9 microns. The refractive index of gallium nitride and sapphire substrate is set to 2.4 and 1.7 respectively. All around the model are perfectly matched layer (PML). The intensity detector is placed one wavelength above the top of the p-type gallium nitride. Due to the fact that the thickness of the light emitting layer is very small compared with the thickness of the gallium nitride layer, the thickness of light emitting layer is set to zero, we just place the simulated light source on the dotted line in this picture.

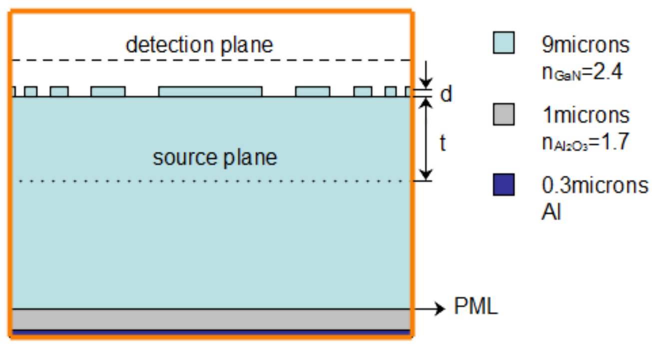


Figure.1. Schematic of the integrated GaN-based blue LED, in which d is the depth of the Fresnel lens and t is the thickness of p-type gallium nitride layer.

According to the grating diffraction equation

$$d(n_1\sin\theta_1-n_0\sin\theta_0)=\lambda$$

In this equation, the wavelength of the incident light is 465 nanometers, and the $n_1$ is the refraction index of the gallium nitride. When d is about 300 nanometers, the output beam can be collimated.

Than the Fresnel lens structure can be designed. Here, considering the size of the structure, the focal length of the Fresnel lens is set to 3 microns. According to the formula that calculates the circle radius of Fresnel lens, the cycle at the edge of this Fresnel lens is designed as 300 nanometers in this model, which conforms to the grating diffraction equation. Otherwise, as a result of the diffraction effects, the photons trapped in the interface of air and gallium nitride can also smoothly exit, so that the light extraction efficiency can be improved. The magnification of light intensity and the change of scattered angle are calculated while this structure has different depth of Fresnel lens (d), thickness of the p-type gallium nitride layer (t), wavelength of light source and the size of light source (s). An expanded gauss light source whose divergence angle is 40 degrees is firstly placed in the middle of the surface of light source, and then, the expanded gauss light source will be moved in the plus and minus x axis direction and get the simulation results respectively, each simulation result will be put together to get the final result.

## 3. RESULTS

In order to get the best combination of depth of Fresnel lens and thickness of p-type gallium nitride layer, multiply results were calculated. Figure.2 shows the magnification of far field intensity distribution with different d and t. In fact, wider variation range of d and t is choused in this simulation, but only some representative results are placed here. From these pictures, it can be seen that light intensity changed with different d and t. In this picture, each line has a peak, and these peaks respectively corresponding to six d, t combination, they are (0.18,7.0), (0.18,6.8), (0.18,6.6), (0.20,6.4), (0.20,6.2), (0.18,6.0), among these six points, when d=0.18 microns and t=6.6 microns, the largest magnification of light intensity can be obtained, which is 4.89 times. Then the far field light intensity is simulated under this circumstance. Figure.3 shows the simulation result compared with the conventional LED.

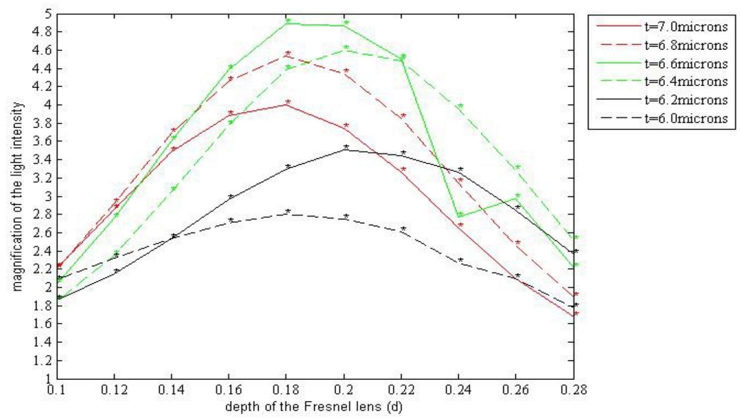


Figure.2. The relationship between the depth of Fresnel lens, the thickness of p-type gallium nitride layer and the magnification of light intensity.

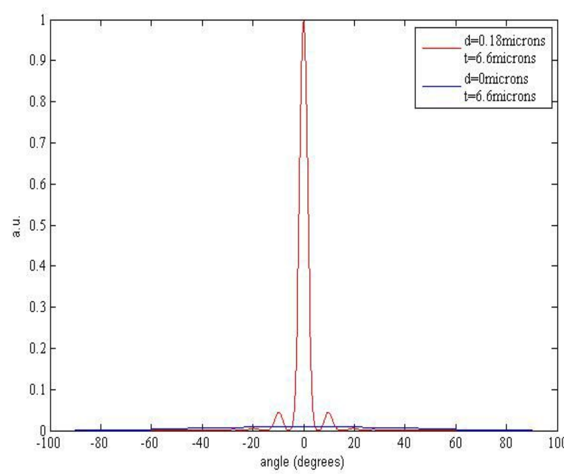


Figure.3. Simulated far field intensity profiles computed with samples with (red line) and without (blue line) Fresnel lens. The scattered angle can be narrowed to 10 degrees.

All these simulation results showed above are attained in the case that the wavelength of light source is 465 nanometers, but in the actual situation, the luminescence spectrum of the GaN-based LED has a certain range. In order to reflect the real situation, the light source is set as a compound light source whose wavelength ranging from 420 nanometers to 495 nanometers. Then, the far field light intensity distribution is simulated and the magnification of light intensity is calculated separately. Figure.4 shows the far field light intensity profile. It can be seen that some lines have two peaks under such simulation circumstances and when d=0.18 microns and t=7.0 microns, the output beam can still be collimated. The specific calculation results of magnification are listed in Table.1. The largest magnification is attained just right to the d and t where the beam can be collimated, which is 3.5 times larger than a conventional LED.

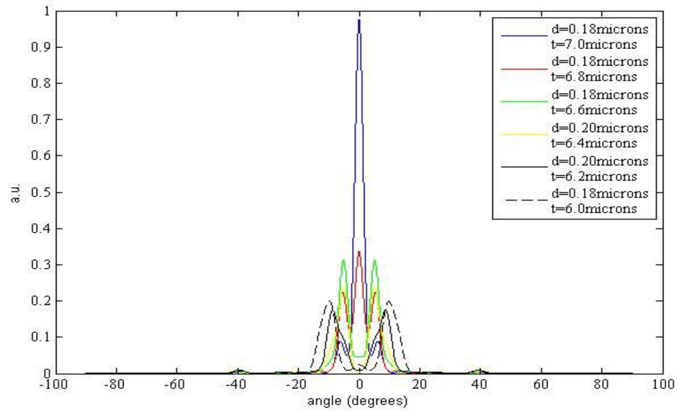


Figure.4. Simulated far field intensity distribution when the wavelength of light source range from 420 nanometers to 495 nanometers.

Table.1. Magnification of light intensity computed with the certain d and t ， and the wavelength of light source ranging from 420 nanometers to 495 nanometers.

| | | | | | | |
|---|---|---|---|---|---|---|
| **d (microns)** | 0.18 | 0.18 | 0.18 | 0.20 | 0.20 | 0.18 |
| **t (microns)** | 7.0 | 6.8 | 6.6 | 6.4 | 6.2 | 6.0 |
| **magnification** | 3.50 | 2.67 | 2.54 | 2.25 | 2.06 | 2.41 |

Finally, the effects that the size of light source made on the scattered angle and the magnification of light intensity were investigated. In real condition, the whole light surface of GaN-based LED will emit photons, so, here a dense array of gauss light sources will take the place of the surface light source of LED. Only one gauss light source was placed each time so as to avoid the interference effect between the light sources. At last, the result of each simulation was added together to get the final result.

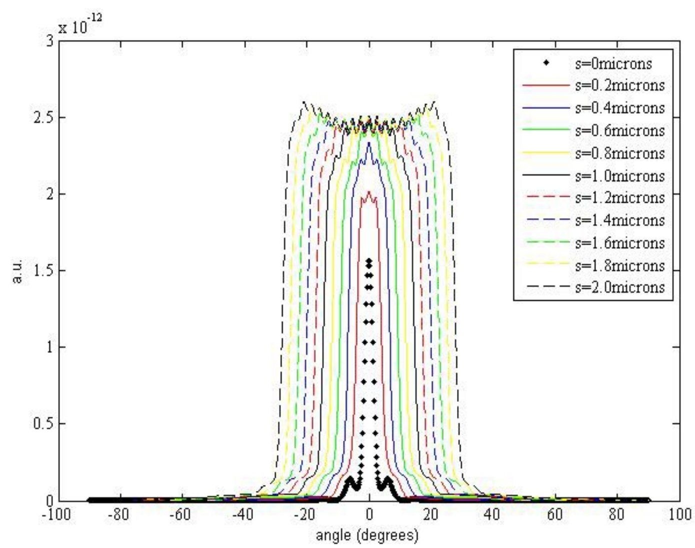


Figure.5. Simulation results with different size of surface light source

Figure.5 reflects the final simulation results. In Figure.5, the black dotted line represents the result when the light source was a gauss source while the red solid line represents the result when the size of the surface light source is 0.2 microns, which contains three single simulation results. It can be seen that the scattered angle of the output beam increased with the size of the light source, but the light intensity were still be improved. This is because the angle of the incident beam and the spatial frequency don’t satisfy the grating diffraction equation when the light sources moving away from the middle position, while the diffraction effect always exists.

## 4. CONCLUSIONS

Through simulation and calculation, it can be find that the magnification of light intensity and the scattered angle both have relationship with the depth of Frsenel lens, the thickness of p-type gallium nitride layer and the wavelength of light source. The trapped photons emit successfully on the interface of air and gallium nitride so that the light intensity can be enhanced. At the same time, such sub-micron Fresnel lens structure can also decrease the scattered angle to some extent. Through simulation, it can be found that the magnification of light intensity can be increased about by3.5 times and the scattered angle can be narrowed to 10 degrees when the depth is 0.18 microns, the thickness is 7.0 microns, the size of light source is about 0.6 microns and the incident light’s wavelength ranges from 420 nanometers to 495 nanometers. It can be said that such GaN-based LED can be used as a projective light source.

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